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Comparative analysis of different grid-independent hybrid power generation systems for a residential load

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ABSTRACT

Demand of electricity is rising all over the world, both in developing and developed countries due to escalation in world population and economic growth. The exploitation of renewable energy is imperative to mitigate energy crisis and to avoid the environmental downfall. The stochastic nature of many renewable energy sources sets techno-economic and functional limitations in their application for covering most types of energy needs. These limitations can be surmounted if a renewable and a conventional energy source are combined to formulate a hybrid generation power system.

This paper examines the techno-economic feasibility of four hybrid power generation systems applied to cover the demand of a typical off-grid residence for a 20 years period. Each one of these hybrid power solutions should involve at least one renewable energy source technology and be able to cover all load needs. Four applications are investigated for each hybrid system, accounting to different geographical areas in Greece with diverse solar and aeolic profile. A comparative analysis is followed to set off the optimal solution based on a minimal total cost criterion.

Contents

1. Introduction

The rising demand of electricity leads to continuous needs and efforts of grid expansion. In many circumstances, the location of the consumers makes their connection to the grid and the fuel transportation uneconomical. The cost of electricity provision at a certain location is determined by various factors such as the installation cost for substations and transmission lines (of high and medium voltage), the size of the load, the terrain complexity etc. An expansion of the electricity grid should follow a coherent, long-term, controlled development while maintaining the security of supply and supporting the functioning of the electricity

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market in the best possible manner. Furthermore, the expansion must take into account the continued technological development, the socioeconomic and environmental aspects, including landscape considerations [1]. Therefore, the viability and efficiency of serving isolated loads with alternative energy options is a considerable topic. In the last decades, grid independent power generation systems based on renewable energy sources (RES) has been studied in numerous R&D projects [2].

Solar energy is an inexhaustible source and its utilization relies on various technologies like solar heaters and photovoltaic systems [3]. Photovoltaic (PV) power generation is a proven method with a vast number of applications across the globe [4]. PV units can be integrated in autonomous or grid-connected systems, covering the electricity demand of various applications. A typical autonomous domestic system, of about 1 kW, may provide electricity for refrigeration, lighting and other low power loads. Similar non-domestic systems can serve loads such as water pumping, telecommunications, etc. On the other hand, grid-connected systems can be utilized in distributed and centralized generation [5,6]. A PV system usually includes, except for the PV arrays, a set of storage batteries, inverters and the power control components.

The operation of PV systems produces zero greenhouse gases emissions, making PV generation an environmental friendly scheme both in urban and rural areas. Additionally, PVs provide a cost-effective and flexible operation option; they can be expanded to meet the growing energy needs. They have no moving parts, a factor which leads to noiseless operation; they are highly portable and have minimal maintenance requirements. Also, their peak power output during summer days often coincides with the peak of load demand. Regarding their limitations, the main drawback is the high initial investment cost. PV power generation is occasionally restricted by local terrain and weather features. Besides that, comparing to other sources, PVs are considered to require a large area per installed kW [7].

Wind energy is a technologically mature, economically competitive and environmental friendly energy source. It was introduced after the first oil crisis as a means that utilizes local sources and enhances energy independence, security and decentralization of the power system [8]. Many countries promote the wind power technology with national programs and market incentives. Wind power is expected to have a significant role in order to address the global challenges of clean energy and sustainable development under climate change [9–11].

Greece specifically has the benefit of high solar and wind capacity. Increased solar radiation and long duration of sunlight, makes it appropriate for the installation of efficient solar technologies. While high altitudes and Southern areas have a slight advantage, all locations within the Greek region are considered attractive for PV installations. Moreover, many areas are characterized by a high aeolic capacity throughout the year, thus, making the utilization of wind energy suitable for serving off grid loads.

The utilization of RES in power generation results in techno-economic drawbacks. Combination with a conventional generation technology always guarantees a stable and reliable method for serving many types of loads. Hybrid power generation systems consist of two or more different types of generation technologies. The aim of this paper is the techno-economic evaluation of a series of hybrid power systems covering the electricity needs of a typical residence. The evaluation refers to the total cost of each configuration, including the initial capital cost, the operational cost, the cost of energy not served, etc. The analysis is carried out by National Renewable Energy Laboratory's (NREL) Hybrid Optimization Model for Electric Renewable© (HOMER©) software. HOMER© is a general-purpose hybrid system framework that facilitates design of electric power systems for stand-alone applications. The software performs automatic sensitivity analysis of the hybrid system design to key parameters, such as the resource availability or component costs. For each scenario, the software displays all the possible configurations (including the installed capacity, the number of battery banks, the number of operational hours, un-met load, etc.) that cover the electricity demands [12].

2. Hybrid power systems design

The absence of continuous availability of some RES brings forth electricity conversion and storage issues. Regarding the photovoltaic and the wind power generation there is a diurnal and a seasonal mismatch between supply and demand. A stand-alone RES based system must have some means of storing energy, which can be used later to supply the load during the periods of low or no power output [13]. The storage issue can be addressed with the use of batteries or the integration of RES with other sources in a hybrid power generation system. Literature shows that the design of a stand alone RES generation plant can lead to an over sizing of the batteries. This problem can be overcome with the combination of RES with a conventional generator technology [14].

Hybrid power systems are combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device. Commonly, hybrid systems involve two or more RES such as PV, wind, small hydro, biomass combined with conventional technologies, such as diesel generators, gas turbines and fuel cells [15]. The design of a stand-alone hybrid system reduces the size of the batteries and offers a solution to the imbalance between supply and demand by the use of a conventional power plant. The operation of a diesel generator (DG) requires the continuous supply with fuel, a fact that may be a drawback in isolated areas, where the fuel transportation is expensive. Moreover, the DG operation produces greenhouse gas. These limitations can be dealt with the combination of DG with a RES [16]. By combining two different generation technologies, the disadvantages of each one can be limited. Therefore, hybrid systems deploy the characteristics of the individual technologies they consist of. They can produce electricity of the same quality as the generators which are components of the electricity grid. Thus not only hybrid systems can be inserted, after the necessary alterations, in thermal power plants providing auxiliary power but also they can be utilized as independent units within mini grids.

Hybrid systems can serve loads where due to their location both the connection with the grid and the fuel transportation are uneconomic. They can serve loads in agriculture areas where the load to be covered is rather small and the expansion of grid is expensive. Ergo, hybrid power plants based on RES is more economical and environmental friendly. Also, hybrid systems provide the potential of a future connection with the grid. Due to their high efficiency and reliability, they can be applicable in cases of power failures and they can serve loads with special needs like hospitals and telecommunication units.

The hybrid systems which are grid connected can serve as independent and continuous generation units and as auxiliary units in cases of peak demand where the cost of the produced kWh is high. Hybrid systems of various capacities have been utilized in developing countries where the rapid growth of load demand undermines grid reliability.

The design of a hybrid system takes into account a number of factors related to:

- the trends of the country's energy policy in the promotion of hybrid power systems and generally, renewable energy technology;
- the size and location of the load: whether it is grid independent or not;

Table 1
Primary energy production, produced electricity and installed capacity per RES in the year 2007.

Source	Primary energy production		Produced electricity		Installed capacity	
	ktoe	%	GWh	%	MW	%
Biofuels	83	4.80	0	0	0	0
Biogas	35	2.00	160	2.99	39	0.97
Biomass	1005	57.60	0	0	0	0
Geothermal	14	0.80	0	0	0	0
Hydro	291	16.70	3377	63.04	3150	77.89
PV	0	0	1.4	0.0003	9	0.23
Solar thermal	160	9.20	0	0	0	0
Wind	156	8.90	1818	33.94	846	20.91
Total	1744	100	5356.50	100	4044	100

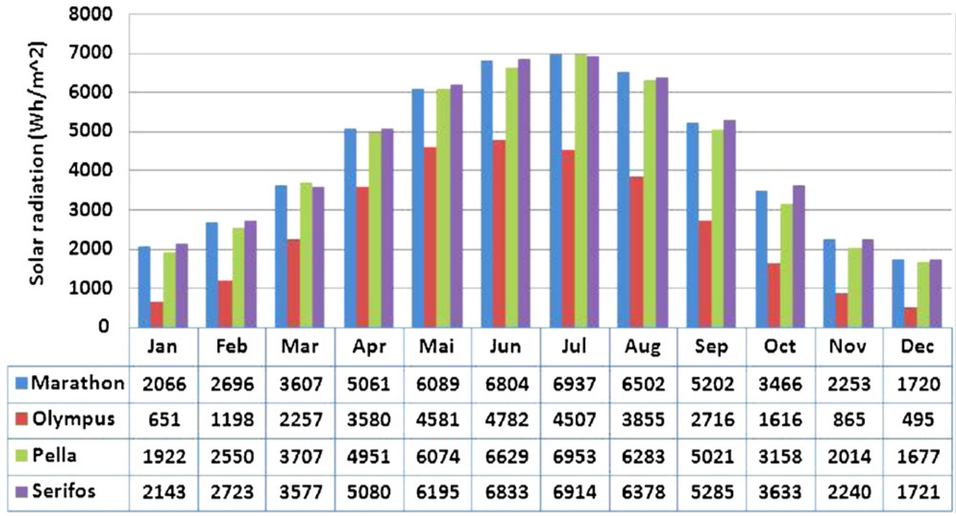

Fig. 1. Average daily solar energy (in Wh/m^2) per month for each site.

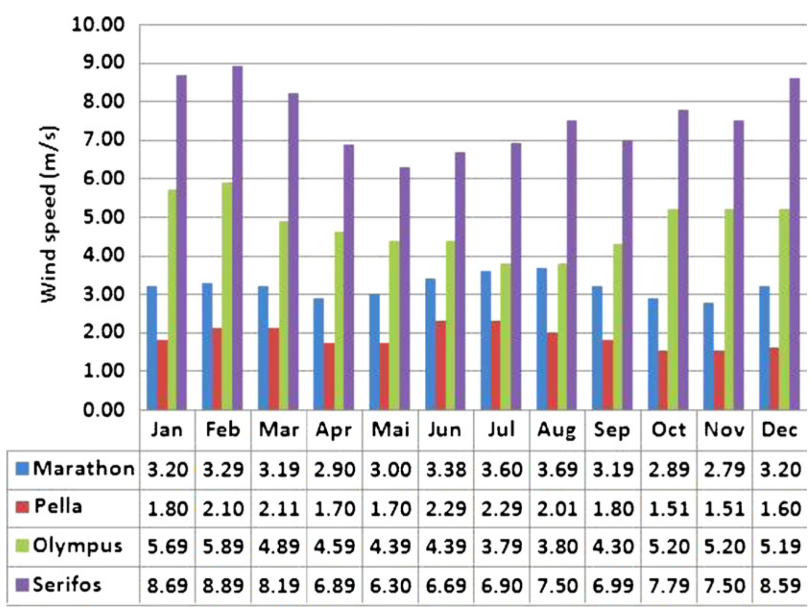

Fig. 2. Monthly average wind speed (m/s) of each region.

- the availability of renewable energy potential and its' share in the overall function of the hybrid system;
- the investment and the operational cost, the function reliability and the environmental impact.

As for the load requirements, the focus of interest is at its peak value and the daily variations. A well designed system should cover the needs without shortages and adjust its function to cover the load variations. Also, the portion of excess energy should be limited. Moreover, the availability of a wide range of meteorological data for the candidate area is important. The accurate data minimize the possibility of a faulty design. Of vital importance is the overall cost including the initial capital, the operation and maintenance (O&M), the cost of produced energy, etc. [17–20].

3. Hybrid power generation in Greece: current status

In the year of 2005, the Greek total primary energy supply reached 31.10 Mtoe. This was an increase of almost 40% over the 22.50 Mtoe of the 1990 level. Primary energy supply had an annual growth of 2.30% for the period 1990–2003 and 1.50% for the period 2004–2010. That was due to the application of energy efficiency policies in commercial and industrial sectors and the further penetration of gas in Greek economy. The fuel mix of primary energy production has witnessed a shift from coal to gas use. Coal accounted for 8 Mtoe in 1990 and 9 Mtoe in 2004, leading to a decrease from 36% to 24% of the fuel mix. Gas share had a growth from 0.60% (12.80 Mtoe) in 1990 to 7.60% (2.35 Mtoe) in 2005. The share of oil in primary energy production had a minor increase from 58% (12.80 Mtoe) in 1990 to 59.50% (19.50 Mtoe) in 2005. The RES share has been stable at 5% between 1990 (1.10 Mtoe) and 2005 (1.60 Mtoe). This mostly reflects the annual water capacity availability for the large hydro plants.

The majority of the electricity in Greece is produced by domestic lignite. The total installed capacity in year 2006 was 13.33 GW where lignite plants accounted for 36.96% of the total. Lignite plants cover the needs of the base loads. The gross electricity generation was 60 TWh, where 54.09% corresponded to lignite plants, 17.39% to natural gas, 14.26% to oil products, 11.27% to large hydro plants, 2.81% to wind power farms and the remaining 0.18% to other RES [21–23].

In the year of 2007, the primary energy production from RES was 1.70 Mtoe and biomass stands for the half of it. The thermal power production comes from the utilization of biomass, especially in residential sector and industry applications, from solar heaters and geothermal units. The growth of the solar heaters industry led Greece to the 2nd place in the installed capacity among the European Union countries.

Table 1 presents the share of each RES to the primary energy production, gross produced electricity and installed capacity mixes [24]. The RES share, with the large hydro plants excluded, in electricity production had a rapid growth due to the continuous installation of small hydro (under 10 MW) and wind farms, i.e., in 1997 the small hydro and wind power plants installed capacity were 43 MW and 27 MW; in 2007, they reached 132 MW and 846 MW, respectively.

The outset of the development of RES in Greece was made by Law 1559/1985 on the "Regulation of matters of alternative forms of energy and specific matters of power production from conventional fuels and other provisions". Until 1995, the Public Power Corporation (PPC) had installed 24 MW of RES while the private sector had no participation. Regarding the development of RES, several other Laws followed (Laws 2244/1994, 2773/1999, 2941/2001 and 3175/2003). Currently, Law 3468/2006 on the "Generation of Electricity using Renewable Energy Sources and High-Efficiency Cogeneration of Electricity and Heat and Miscellaneous Provisions" takes into account the European Commission's Directive 2001/77/EC and assigns the conditions for the installation and operation of RES units [25]. This Directive "on the Promotion of Electricity Produced from Renewable Energy Sources in the Internal Electricity Market", sets in its annex an indicative target for Greece: by 2010, 20.10% of gross national electricity consumption should be covered from RES (including large-scale hydroelectric plants). This target is compatible with the international commitments of the country resulting from the Kyoto protocol signed in December 1997 within the context of the Rio UN framework agreement on climate change. The Kyoto protocol anticipates that Greece, by 2008–2012, will reduce the rate of increase of CO_2 and other gases that aggravate the greenhouse effect by 25% in relation to the base year 1990. The Law 3468/2006 foreshows the legal framework concerning the licensing for installation, generation and operation of the RES units and for the environmental and urban planning issues. Furthermore, the Law determines the renewable energy feed-in tariffs and examines the potential of meeting the EU targets for the year of 2020.

The Law 3468/2006 also determines the operation framework of the hybrid power systems and focuses in the capacity availability billing of the hybrid systems utilized in the grid independent islands of the Greek region. The framework aims at increasing RES integration in hybrid systems into the islands energy mix and reducing conventional fuel consumption.

The 3rd Community Operational Framework Programme "Competitiveness" launched by the Ministry of Development in the period 2000–2006 provided the financing incentives for small autonomous hybrid power plants [26]. Within this framework, a number of 250 PV/DG hybrid systems were installed with an overall capacity of 2.20 MW. The majority of these systems were set to cover the base transmission stations of mobile telephony companies in remote locations. Currently, many applications for hybrid system installation from various private companies are under evaluation by the Regulatory Authority of Energy. The proposed systems combine WTs and small hydro plants, with an overall capacity of 312 MW and 319 MW, respectively. One hybrid system is under construction by the PPC Renewables S.A. in Ikaria Island, involving 2.40 MW of WTs and 3.80 MW of small hydro plants [27].

4. Study case

The aim of this paper is to examine the economic viability of various grid independent hybrid power systems in four Greek regions covering the electrical needs of a typical residence. The mean annual electrical energy demand is 7008 kWh, while the daily average is 19.20 kWh/day. Four hybrid configurations were formulated and applied in each region separately for 20 years' duration.

The four regions which were taken into account are Pella, located in the north (latitude 40°48′N, longitude 22°03′E), an area on the mountain Olympus located in north central Greece (39°55′N, 22°25′E), Marathon, very close to the urban area of Athens (38°23′N, 22°13′E) and Serifos, an Aegean island with the highest aeolic capacity within the Greek region (37°30′N, 25°9′E). The average daily solar energy (in Wh/m^2) per month and the average monthly wind speed (in m/s) of each region are shown in Figs. 1 and 2, respectively. The data has been obtained by the METEONORM 6.1© platform, developed by METEOTEST [28].

5. Hybrid power systems configurations

5.1. Techno-economic data

The hybrid systems that were applied to cover the electrical needs of the residence combine the following technologies:

- Photovoltaic and diesel generator
- Photovoltaic and wind turbine
- Wind turbine and diesel generator
- Wind turbine and fuel cell

Each system includes a set of batteries, an inverter and where applicable, a reformer and a hydrogen tank. The single PV panel capacity is 0.155 kW and the array's total installed capacity is allowed to vary from 0.31 kW to 10.23 kW. Four sizes of available wind turbines are considered, 0.6 kW, 1.50 kW, 3 kW and 6 kW. Two types of commercial single phase DG are considered, with capacities of 3.70 kW and 5.70 kW. Regarding the fuel cells, three types are considered with installed capacities of 0.50 kW, 1 kW and 2 kW.

5.2. Photovoltaic–diesel generator hybrid power system

A significant factor which influences the total cost of a DG is the fact that the price of crude oil is rising continuously. Moreover, a daily use of a DG for the production of electric power results in increased needs for maintenance and replacement of the generator itself. The initial investment cost may include the fuel distribution cost. In contrary with the relatively low cost of acquisition, a DG has high maintenance cost and given the negative environmental impact; the option of a system based solely on a DG is disadvantageous. Another characteristic of the DG is its efficient operation in load conditions around 70–80% of its capacity. If the load falls below the 50% of the capacity, the operational cost and the fuel inefficiency can lead to a high cost of produced electricity. The drawbacks can be overcome by integrating a DG together with a PV unit and a set of batteries in a hybrid system.

The chosen capacity of the DG is determined by size of the load. First of all, the DG must satisfy the peak of the load. Also the type of the load is an important factor. For example, if the load is of resistive nature, there is no necessity for stabilized frequency. In that case, a design technique can be selected for the hybrid system, where the inverter does not work simultaneously with the DG and the power of the inverter depends on the capacity of the batteries. Another option is the use of two converters in order to form a double direction converter, a scheme that is very common in PV/DG systems. If the capacity of the batteries cannot meet the load peak through the inverter, then the inverter may have a smaller capacity and the peak load can be covered directly from the DG. When the requirements of the load impose steady frequency then the frequency of the load must be assigned from the output of the inverter. The latter case is the most expensive.

The schematic of the PV/DG system and the corresponding energy flow are shown in Fig. 3.

The operation of the system is the following: the PV supplies the load through the converter. The exceeding electricity charges the batteries through the charge regulator until the batteries reach the maximum permitted level of charge. The main purpose of the battery use is to supply or to save electricity according to the demand. The DG operates when the PV and the batteries cannot satisfy the load demand. Literature shows that the DG/PV hybrid system is a favorable generation option for remote areas. Numerous applications have been installed around the globe, covering different classes of applications.

5.3. Photovoltaic–wind turbine hybrid power system

A mere RES hybrid system is the combination of a set of PVs with a WT [29]. The performance of such systems depends on local weather variations. The optimized combination of the two technologies limits the inefficiencies of the sole operation of each one. There are periods within the year that the operation of PV or the WT alone is adequate. For example, aeolic capacity is commonly high in winter where the duration of sunlight is low, thus making appropriate the use of WT instead of the PV units.

Autonomous RES or integrated in hybrid power systems are the common ways of electrification of developing regions. The main problem is their complexity, i.e., the use of two different kinds of RES means a more difficult, stochastic analysis of the hybrid system. Taking into consideration the available solar and aeolic capacities, the designer of the hybrid system must decide on the best sizing for PV units and WT.

The evaluation of the aeolic capacity of a region is a complicated process because the wind is affected by many ways such us: the installation site, the ground morphology, the possible obstacles (trees, buildings) and other local parameters. The absence of meteorological data can lead to a total false selection of power of the generator and a possible economic failure. Consequently, for the assessment of the aeolic capacity, the knowledge of the medium wind velocity for the wider area is not enough. On-Field or nearby measurements and a reliable model are needed to estimate the wind rose or the duration curve for local, exploitable wind potential, it's diurnal and seasonal profile.

Fig. 4 shows the energy flow of the system. During the operation of the hybrid power system, the following conditions can be distinguished:

- If load demand is lower than WT output, the excess electricity and the PV produced electricity are stored through the converter and the charge regulator to the battery banks.
- If load demand is higher, the PVs cover the load through the converter.
- If load demand cannot be covered by both RES, the batteries are set to cover the demand only if they are charged more than the lower permitted level of charge.

The operation of the regulator is to prevent the situation of a lower and upper level of charge of the batteries.

5.4. Wind turbine–diesel generator hybrid power system

In this configuration, the emphasis was placed in the factors that influence the design options for the DGs and the WTs [30,31]. Therefore, a number of DGs and WTs together with batteries were tested. The sophisticated design of a WT/DG system eliminates the situations of under- and over-sizing. An under-sized system is likely to provide a fluctuating power production with different peaks. Occasionally, the selection of DG with installed power twice the peak load is appropriate in order to cover a future load installation enlargement.

The design options of the WT are the following:

- The installed capacity of the WT must be equal with the capacity of the DG and the size of the load.
- There is a dissension among scholars if it is appropriate to utilize a large WT or a number of smaller ones [32].

A system with large installed capacity and a number of WTs and DGs offers several advantages as:

- There is a number of DGs which provides the option of choice of which DG will operate and hence, the fuel consumption is minimized.
- Since the WTs are installed in different positions, slight differences of wind power outputs are expected. This can also lead to a smoother sum output.
- In cases of maintenance and replacement of the systems parts, the situation of not meeting the demand due to a lack of production capability is minimized.

The schematic of the hybrid system is shown in Fig. 5.

During normal operation, the WT covers the load demand. When there is excess electricity, it charges the batteries through a charge regulator until their upper nominal level. In the case of a full charge, the excess electricity goes unused. The DG operates only if the WT along with the batteries cannot meet the load demand.

5.5. Wind turbine–fuel cell hybrid power system

The aim of the WT/FC generation scheme is to optimize the usage of the wind energy in an autonomous system [33,34]. The wind power is strongly dependent on the meteorological conditions

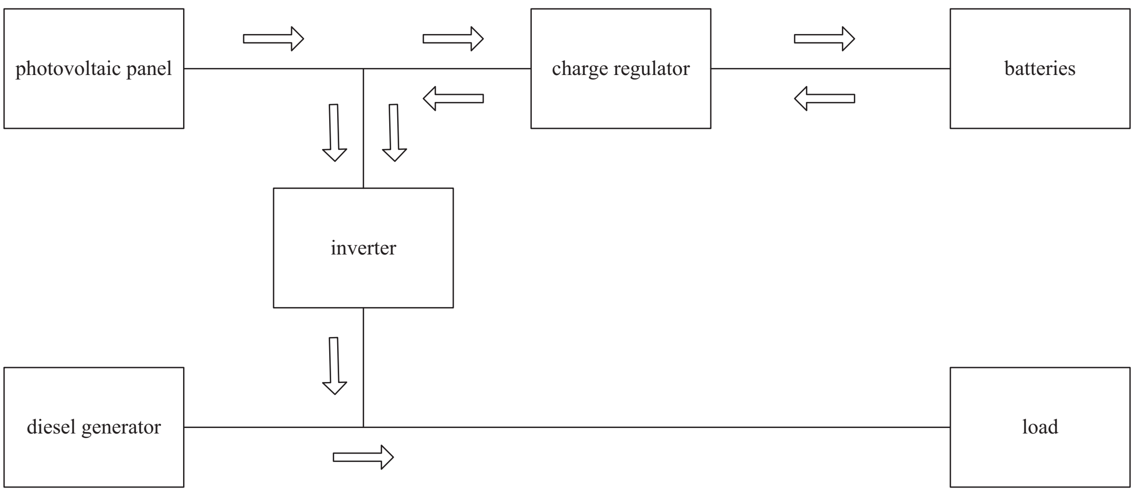

Fig. 3. Energy flow in the PV/DG hybrid power generation system.

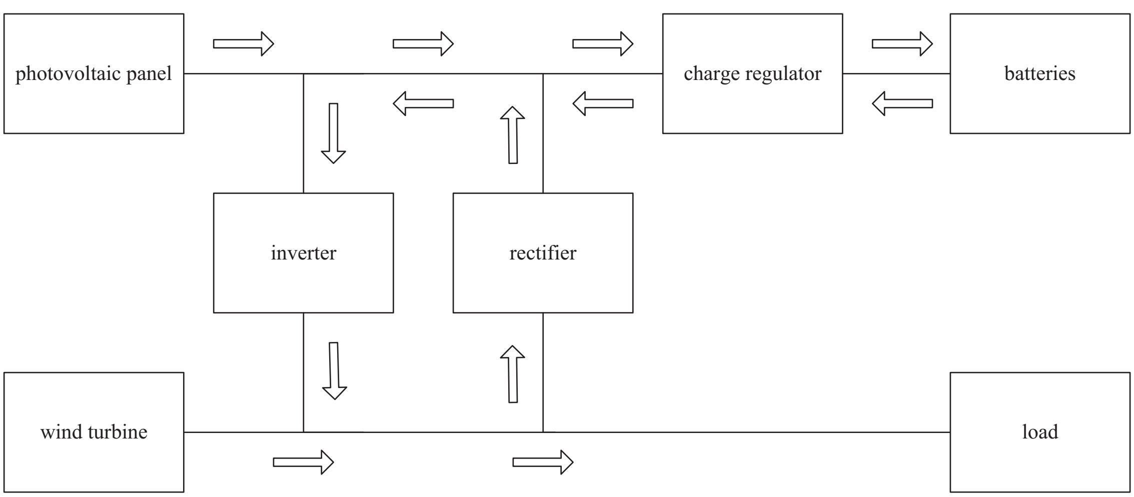

Fig. 4. Energy flow in the PV/WT hybrid power generation system.

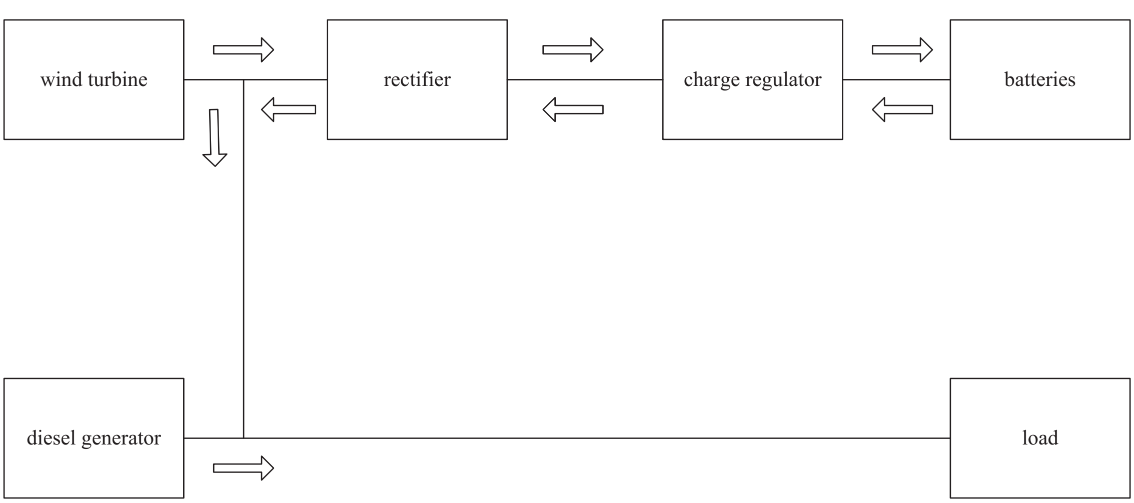

Fig. 5. Energy flow in the WT/DG hybrid power generation system.

resulting to an unbalance between generation and demand. Additionally, in cases of low demand, part of the produced electricity cannot be absorbed. In this hybrid scheme, a significant stabilization of the power that a wind generator produces is achieved through the storage facility. The stored electricity is utilized in periods of low winds or in cases of high demand. The hybrid system involves the usage of hydrogen as a fuel in the FC. Hydrogen is produced through the reforming of natural gas. The study does

Table 2
Techno-economic characteristics of the optimal PV/DG hybrid systems in the four regions.

PV/DG hybrid system										
Optimal system	PV (kW)	DG (kW)	Batteries (kWh)	Converter (kW)	Operating cost (€/year)	NPC (€)	COE (€/kWh)	Renewable fraction	Fuel (L/year)	DG (h/year)
Marathon										
1	3.72	3.70	32.4	3.50	1872	43,252	0.495	0.61	1082	901
2	4.03	5.70	33.6	3.50	1844	44,182	0.506	0.66	1039	651
3	3.72	3.70	0	3.50	4883	76,717	0.878	0.39	3981	6711
Olympus										
1	3.10	3.70	34.8	3.50	2803	53,287	0.610	0.28	2036	1668
2	3.10	5.70	36	3.50	2940	55,360	0.634	0.27	2180	1359
3	4.03	3.70	0	3.50	5483	85,126	0.975	0.25	4515	7608
Pella										
1	4.03	3.70	37.2	3.50	1758	43,356	0.496	0.66	961	800
2	4.34	5.70	33.6	3.50	1784	44,367	0.508	0.69	954	604
3	3.1	3.70	0	3.50	5028	76,667	0.878	0.34	4164	7026
Serifos										
1	4.03	3.70	36	3.50	1758	43,207	0.495	0.66	960	802
2	4.34	5.70	33.6	3.50	1777	44,276	0.507	0.69	945	600
3	3.72	3.70	0	3.50	4897	76,892	0.880	0.39	3994	6736

Table 3
Techno-economic characteristics of the optimal PV/WT hybrid systems in the four regions.

PV/WT hybrid system						
PV (kW)	WT (kW)	Batteries (kWh)	Converter (kW)	Operating cost (€/year)	NPC (€)	COE (€/kWh)
Marathon						
7.44	6	93.6	3.50	1237	66,611	0.763
Olympus						
0.31	6	91.2	3.50	637	37,435	0.429
Pella						
8.99	3	110.4	3.50	1328	70,608	0.809
Serifos						
0.62	6	82.8	3.50	596	32,924	0.377

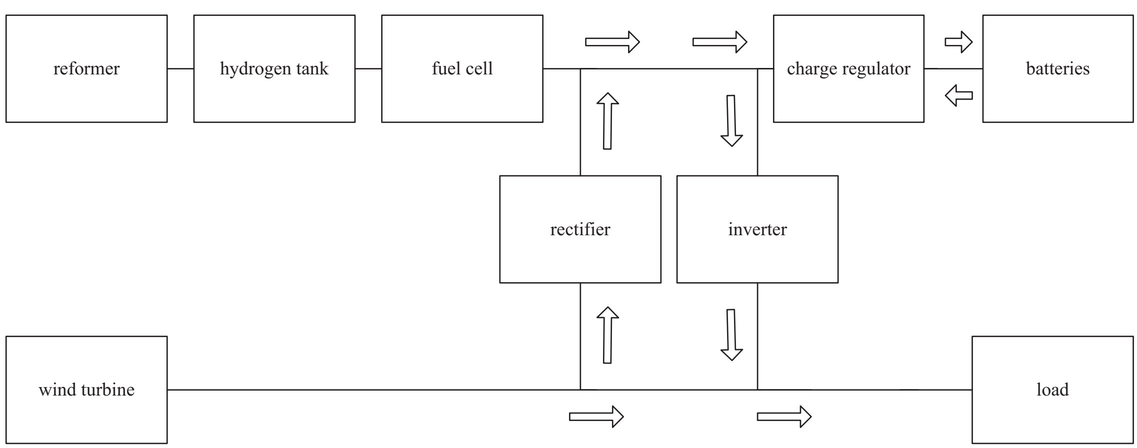

Fig. 6. Energy flow in the WT/FC hybrid power generation system.

not take into account the method which the natural gas is supplied to the hybrid system and hence, the cost of this process is not included to the total cost of the hybrid system. The hydrogen acts as storage mean of the surplus electricity that comes from the WT.

The design options of the system (size of the hydrogen tank, reformer, capacity of the FC) depend on the level of "hybridism", i.e., the ratio between the electricity produced directly from the WT to that produced by the FC alone. The main advantage of the WT/FC system is the high efficiency of the operation and the zero gases emissions. This system can also produce a significant amount of heat due to the FC operation, and this amount can serve in space heating or other applications.

Fig. 6 presents the energy flow of the WT/FC hybrid system.

The operation of the system involves the supply of the reformer with natural gas which is converted into hydrogen and then stored in a high pressure hydrogen tank. The reformer uses electric power from the WT to make the conversion. When there is no wind the hydrogen is converted into electric energy through the FCs and so there is a constant flow of energy to the load. The fuel cells supply the load with stable electricity, independently of the wind fluctuations. There is a possibility of simultaneous additional power production, in case the operating temperature of the FC produces steam of high energy content. In the cases that this paper examines there is no such potential because of the low operational temperature of the FCs considered.

Table 4
Techno-economic characteristics of the optimal WT/DG hybrid systems in the four regions.

WT/DG hybrid system										
Optimal system	WT (kW)	DG (kW)	Batteries (kWh)	Converter (kW)	Operating cost (€/year)	NPC (€)	COE (€/kWh)	Renewable fraction	Fuel (L/year)	DG (h/year)
Marathon										
1	6	3.70	39.6	3.50	1406	40,173	0.460	0.77	835	715
2	6	5.70	43.2	3.50	1403	40,798	0.467	0.78	855	562
3	6	3.70	0	3.50	4710	76,405	0.875	0.51	3927	6667
Olympus										
1	6	3.70	25.2	3.50	1037	33,775	0.387	0.91	508	430
2	6	5.70	27.6	3.50	1041	34,337	0.393	0.91	522	326
3	6	–	94.8	3.50	615	36,680	0.420	1.00	–	–
Pella										
1	6	3.70	33.6	3.50	2593	54,213	0.621	0.37	1896	1575
2	6	5.70	36	3.50	2677	55,767	0.639	0.37	1995	1214
3	6	3.70	0	3.50	5545	86,803	0.994	0.26	4705	7940
Serifos										
1	3	3.70	21.6	3.50	849	27,107	0.310	0.92	385	330
2	3	5.70	21.6	3.50	852	27,355	0.313	0.92	397	248
3	6	–	68.4	3.50	586	33,024	0.378	1.00	–	–

Table 5
Techno-economic characteristics of the optimal WT/FC hybrid systems in the four regions.

WT/FC Hybrid system													
Optimal system	WT (kW)	FC (kW)			Batteries (kWh)	Converter (kW)	Operating cost (€/year)	NPC(€)	COE (€/kWh)	Natural gas (m^3)	FC (h/year)		
Marathon													
1	6	–	–	2	36	3.50	1212	48,069	0.551	709	–	–	1150
2	6	0.50	–	2	36	3.50	1178	48,402	0.554	708	840	–	939
3	6	–	1	2	33.6	3.50	1166	48,702	0.558	717	–	1387	469
Olympus													
1	3	–	–	2	28.8	3.50	1114	42,074	0.482	676	–	–	1097
2	3	0.50	–	2	31.2	3.50	1077	42,668	0.489	671	915	–	861
3	6	–	1	2	26.4	3.50	1094	43,021	0.493	707	–	1440	427
Pella													
1	–	0.50	1	2	10.8	3.50	2827	54,305	0.622	2402	3896	3876	975
2	–	–	1	2	19.2	3.50	2870	55,141	0.631	2453	–	4271	1828
3	0.60	0.50	1	2	10.8	3.50	2803	57,954	0.664	2325	3949	3710	914
Serifos													
1	3	–	–	2	19.2	3.50	711	35,854	0.411	302	–	–	494
2	3	0.50	–	2	16.8	3.50	720	36,416	0.417	327	481	–	414
3	3	0.5	1	–	43.2	3.50	606	36,793	0.422	121	377	215	–

6. Results

Each scenario refers to one of the regions under consideration. Each system was applied separately leading to the formulation of 16 test cases. The systems of the same hybrid configuration, i.e., WT/DG, differs at each region in terms of the number and size of the components of the main technologies (WTs and DGs), the number of batteries, the capacities of inverter, rectifier and other components. The optimal configuration for each region is exported due to the total cost and not due to the amount of excess electricity. The excess electricity is the surplus electrical energy that must be dumped because it cannot be used to serve a load or charge the batteries. It occurs when there is a surplus of power being produced (either by a renewable source or by the generator when its minimum output exceeds the load) and the batteries are unable to absorb it all. The excess electricity can be used to serve a thermal load by means of resistive heating. In case of grid connection, the surplus energy can be supplied to the grid. The excess electricity could be limited if RES capacity was lower or batteries' capacity was higher. Nevertheless, such option would lead to increased capital and O&M costs.

The economic evaluation refers to a life cycle cost (LCC) analysis for each hybrid system [17]. The LCC analysis aids to the comparison of systems that provide equal energy result, which is the covering of the daily load. With the LCC analysis the optimal techno-economic option can be defined. More specifically, the LCC analysis calculates the net present value all of the expected costs (NPC) during the projects lifetime. Some of these costs cannot be predicted accurately; therefore a sensitivity analysis must be carried out. The sensitivity analysis concerns the fuel cost, the replacement and the maintenance costs. The LCC of an investment can be defined as:

$$\mathrm{LCC} = C + M_{PV} + E_{PV} + R_{PV} - S_{PV} \tag{1}$$

where C is the initial capital cost, M_{PV} is the operation and maintenance cost (O&M), E_{PV} is the fuel cost, R_{PV} is the replacement cost and S_{PV} is the salvage value. The initial capital cost includes the cost of purchasing the equipment and the installation cost. The O&M cost is the sum of all the programmed expenses for the operation and maintenance of the project lifetime. Finally, the salvage value is the value remaining in a component of the power system at the end of the project lifetime.

In the above equation, the indication "*PV*" refers to present value of every factor. The present value is the equivalent value at the present of a set of future cash flows, taking into account the time value of money. Because there is no sale of the produced electricity back to the electricity grid and thus, there is no corresponding income, the techno-economic evaluation takes into account the Net Present Cost (NPC) of the hybrid systems, which is the present value of all the costs that it incurs over its lifetime, minus the present

Table 6
Cost analysis of the optimal hybrid systems in the Marathon region.

PV/DG hybrid system

Cost (€)	PV	DG	Batteries	Converter	System
Installation	11,160	534	4050	4175	19,919
Replacement	0	237	2223	4738	7199
O&M	3888	348	437	0	4674
Fuel	0	12,977	0	0	12,977
Salvage	0	−161	−569	−787	−1517
Total	15,048	13,936	6142	8127	43,252

PV/WT hybrid system

Cost (€)	PV	WT	Batteries	Converter	System
Installation	22,320	12,994	11,700	4175	51,189
Replacement	0	0	0	4738	4738
O&M	7776	2430	1264	0	11,470
Fuel	0	0	0	0	0
Salvage	0	0	0	−787	−787
Total	30,096	15,424	12,964	8127	66,611

WT/DG hybrid system

Cost (€)	WT	DG	Batteries	Converter	System
Installation	12,994	534	4950	4175	22,653
Replacement	0	0	2022	4738	6760
O&M	2429	276	535	0	3240
Fuel	0	10,014	0	0	10,014
Salvage	0	−9	−1698	−787	−2494
Total	15,423	10,815	5809	8127	40,173

WT/FC hybrid system

Cost (€)	WT	FC (2 kW)	Batteries	Converter	Reformer	Hydrogen tank	System
Installation	12,994	3000	4500	4175	5000	3300	32,969
Replacement	0	1588	1789	4738	0	0	8115
O&M	2429	444	486	0	1246	0	4606
Fuel	0	0	0	0	5917	0	5917
Salvage	0	−528	−1598	−787	−377	−249	−3538
Total	15,423	4504	5178	8127	11,787	3051	48,069

value of all the revenue that it earns over its lifetime. The NPC is given by the following equation:

$$C_{\text{NPC}} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{2}$$

where $C_{ann,tot}$ is the total annualized cost (€/year), CRF is the capital recovery factor, i is the interest rate (%) and R_{proj} is the project lifetime (yr). The total annualized cost is the sum of the annualized costs of each system component (annualized capital, replacement, O&M and annual fuel costs). The capital recovery factor is a ratio used to calculate the present value of a series of annual cash flows. It is defined as:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

where i is the interest rate (%) and N is the number of years. The interest rate that HOMER® takes into account is the annual real interest rate which is the discount rate used to convert between one-time costs and annualized costs. The project lifetime is the length of time over which the costs of the system occur.

The operating cost is the annualized value of all costs (replacement, fuel, O&M) and revenues other than initial capital costs. HOMER® uses the following equation to calculate the operating cost:

$$C_{\text{operating}} = C_{ann,tot} - C_{ann,cap} \tag{4}$$

where $C_{ann,tot}$ is the total annualized cost (€/year) and $C_{ann,cap}$ is the total annualized capital cost (€/year).

Another factor that assists at the techno-economic evaluation is the cost of energy (COE). The cost of energy is defined as the average cost per kWh of useful electrical energy produced by the system. To calculate the cost of energy, HOMER® divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load, if any) by the total useful electric energy production.

The optimal PV/DG, PV/WT, WT/DG and WT/FC configurations in the four regions are shown in Tables 2–5, respectively.

The systems are classified in terms of the value of the NPC. HOMER® lists all the possible configurations that can cover the load demand. Tables 2, 4 and 5 present the three configurations that have the lower NPC. The simulation results propose only one optimal PV/WT hybrid system in each region, as shown in Table 3. For all systems, the minimal value for the renewable fraction, which is defined as the portion of the system's total energy production originating from renewable power sources, was set to be at 0.25. All the configurations involve a 3.50 kW converter (rectifier and inverter), sized according to the peak load of the residence. The daily peak load has an average value of 3.32 kW.

6.1. Marathon region

In the Marathon region the optimal PV/DG system involves a 3.72 kW PV together with a 3.7 kW DG and 32.4 kWh of batteries. This system has an NPC of 43,252 €, a COE of 0.495 €/kWh and an operating cost of 1872 €/year. DG operates 901 h/year and the total fuel requirement is 1082 L/year.

Table 7
Cost analysis of the optimal hybrid systems in the Olympus region.

PV/DG hybrid system

Cost (€)	PV	DG	Batteries	Converter	System
Installation	9300	534	4350	4175	18,359
Replacement	0	566	2397	4738	7702
O&M	3240	644	470	0	4354
Fuel	0	24,408	0	0	24,408
Salvage	0	−156	−594	−787	−1537
Total	12,540	25,997	6623	8127	53,287

PV/WT hybrid system

Cost (€)	PV	WT	Batteries	Converter	System
Installation	930	12,994	11,400	4175	29,499
Replacement	0	0	0	4738	4738
O&M	324	2429	1231	0	3984
Fuel	0	0	0	0	0
Salvage	0	0	0	−787	−787
Total	1254	15,423	12,631	8127	37,435

WT/DG hybrid system

Cost (€)	WT	DG	Batteries	Converter	System
Installation	12,994	534	3150	4175	20,853
Replacement	0	0	1204	4738	5943
O&M	2429	166	340	0	2935
Fuel	0	6086	0	0	6086
Salvage	0	−86	−1170	−787	−2042
Total	15,423	6700	3525	8127	33,775

WT/FC hybrid system

Cost (€)	WT	FC (2 kW)	Batteries	Converter	Reformer	Hydrogen tank	System
Installation	9117	3000	3600	4175	5000	3300	28,192
Replacement	0	1540	1462	4738	0	0	7740
O&M	1704	424	389	0	1246	0	3763
Fuel	0	0	0	0	5643	0	5643
Salvage	0	−608	−1244	−787	−377	−249	−3264
Total	10,821	4356	4206	8127	11,512	3051	42,074

The second best configuration involves a 4.03 kW PV along with a 5.7 kW DG and 33.6 kWh of batteries. The NPC of this solution is slightly worse (2%) than the optimal, thus what is gained in fuel cost, is lost in initial capital cost.

The third configuration has a 3.72 kW PV, a 3.7 kW DG and no batteries. Its' high NPC value (77% increased compared with the optimal) shows the importance of storage batteries.

The optimal PV/WT hybrid system involves a double PV capacity and a triple capacity of batteries comparing to PV/DG. Thus replacing DGs with WTs in this area of low wind potential results in a 50% increased NPC value.

Apparently the WT/DG hybrid is the best solution, slightly better than PV/DG. It is interesting that WT/DG hybrid systems are generally the most preferable case, even for low-medium wind speeds (of an average value more than 3.5 m/s).

Finally, the WT/FC systems include a significant smaller number of batteries in comparison with the other configurations, due to the smaller size of the WT. Many WT/FC systems utilize two or more FCs with different capacities. Most of generated electricity comes from the FCs. The three optimal systems have almost equal COE resulting to almost equal NPC. Also, all systems have identical annual natural gas consumption.

6.2. *Olympus region*

The application in Olympus region is a case of lower solar capacity, due to frequent cloudiness and partial shading caused by the huge nearby massif; The optimal PV/DG system has an NPC of 53,287 € and a COE of 0.61 €/kWh. It is composed by a set of panels with aggregated installed capacity of 3.1 kW, a DG of 3.70 kW and 34.8 kWh of batteries. Due to poor solar potential, the DG has a significantly higher (almost doubled) fuel cost in the Olympus region because of increased DG operating hours per year.

Due to Olympus high aeolic potential, the PV/WT system involves a 6 kW WT and a negligible PV capacity (0.31 kW). The aforementioned system has a relatively low NPC compared to the PV/WT systems of the other regions.

The high aeolic capacity also results in a high renewable fraction of the WT/DG optimal systems. Most part of produced electricity (∼90%) comes from the WT and this leads to limited fuel consumption and therefore a low COE. Also, the small number of the necessary batteries leads to a relatively low NPC.

Additionally, a high energy contribution of WT (70%) is found in the WT/FC systems. The optimal configuration is composed of a 3 kW WT along with FC of 2 kW. The three optimal systems do not differ much in their techno-economic characteristics.

6.3. *Pella region*

The region of Pella is similar with the region of Marathon but an evident difference is its very low wind potential. The optimal PV/DG configuration is consisted of a 4.03 kW PV, a 3.70 kW DG and 37.2 kWh of batteries. It has an NPC of 43,356 € and a COE of 0.496 €/kWh. These values are comparable with the PV/DG systems of the other regions which have identical solar capacities.

Table 8
Cost analysis of the optimal hybrid systems in the Pella region.

PV/DG hybrid system

Cost (€)	PV	DG	Batteries	Converter	System
Installation	12,090	534	4650	4175	21,449
Replacement	0	214	2364	4738	7316
O&M	4212	309	502	0	5024
Fuel	0	11,520	0	0	11,520
Salvage	0	−188	−978	−787	−1952
Total	16,302	12,389	6538	8127	43,356

PV/WT hybrid system

Cost (€)	PV	WT	Batteries	Converter	System
Installation	26,970	9117	13,800	4175	54,062
Replacement	0	0	0	4738	4738
O&M	9397	1707	1490	0	12,594
Fuel	0	0	0	0	0
Salvage	0	0	0	−787	−787
Total	36,367	10,824	15,290	8127	70,608

WT/DG hybrid system

Cost (€)	WT	DG	Batteries	Converter	System
Installation	12,994	534	4200	4175	21,903
Replacement	0	546	2327	4738	7611
O&M	2430	608	454	0	3492
Fuel	0	22,725	0	0	22,725
Salvage	0	−181	−551	−787	−1519
Total	15,424	24,233	6429	8127	54,213

WT/FC hybrid system

Cost (€)	FC (0.5 kW)	FC (1 kW)	FC (2 kW)	Batteries	Converter	Reformer	Hydrogen tank	System
Installation	750	1500	3000	1350	4175	5000	3300	19,075
Replacement	2203	4410	1416	745	4738	0	0	13,512
O&M	1495	1497	377	146	0	1246	0	4761
Fuel	0	0	0	0	0	20,052	0	20,052
Salvage	−238	−470	−791	−183	−787	−377	−249	−3095
Total	4210	6937	4001	2058	8127	25,921	3051	54,305

The optimal PV/WT in the Pella region system has the highest NPC of all systems that were considered in this study. Due to low winds, we are driven to double PV and triple batteries capacity and finally to a 63% increased NPC value.

As for the WT/DG systems, the DGs are responsible for the largest amount of the produced electricity. The high fuel consumption is the reason of the increased COE.

An interesting case is met on the synthesis of the optimal WT/FC system. HOMER® proposes the first two optimal systems with an absence of WT. Different combinations of FCs solely cover the electricity needs of the residence. This scheme leads to the higher values of COE among all the WT/FC systems of all regions. Only the third optimal system involves a WT with a comparatively low installed capacity.

6.4. Serifos island

The island of Serifos has the highest aeolic capacity within Greek region. It is considered in this study in order to test the potential of a vast utilization of the WT technology.

The optimal PV/DG system of the Serifos region does not differ much compared to the regions of Marathon and Pella where solar conditions are similar.

The PV/WT system makes an intense use of the WTs which have a 10-fold installed capacity comparing to PVs.

In the same way, in the WT/DG and WT/FC systems the WT energy contribution rises up to 90%. The WT/DG case is the overall best solution with an NPC of 27,107 € and a COE of 0.31 €/kWh.

6.5. Cost of components

The cost apportionment of the various components of the optimal hybrid system in the four regions is presented in Tables 6–9.

The cost apportionment takes into account the installation cost, the replacement cost, the operation and maintenance (O&M) cost, the fuel cost and the salvage value. Salvage value is the value remaining in a component of the power system at the end of the project lifetime. HOMER® assumes linear depreciation of components, meaning that the salvage value of a component is directly proportional to its remaining life. It also assumes that the salvage value is based on the replacement cost rather than the initial capital cost.

Table 6 refers to the Marathon region. It can be noticed that the RES technologies have a high installation cost and a considerable O&M cost. Their replacement cost is zero. This is due to the fact that the systems lifetime is higher than the period of the 20 years that is considered in this study. The commercial DGs and FCs that are incorporated have notable replacement and O&M costs. In addition, their contribution to the total cost is worth notice, taking into account fuel cost.

Table 7 refers to the Olympus region, Table 8 to the Pella region and Table 9 to the Serifos region. Regarding the optimal PV/DG systems, the installation cost has usually the largest share, accounting to 46% of NPC in Marathon region, 34% in Olympus region and 49% of NPC in regions of Pella and Serifos. The fuel cost has the second largest share, usually 25–30% of NPC.

As for the WT/DG, the installation cost has again the largest share of NPC (55–60%). In the WT/FC systems, the presence of the

Table 9
Cost analysis of the optimal hybrid systems in the Serifos region.

PV/DG hybrid system

Cost (€)	PV	DG	Batteries	Converter	System
Installation	12,090	534	4500	4175	21,299
Replacement	0	214	2313	4738	7265
O&M	4212	310	486	0	5008
Fuel	0	11,515	0	0	11,515
Salvage	0	−187	−906	−787	−1880
Total	16,302	12,386	6393	8127	43,207

PV/WT hybrid system

Cost(€)	PV	WT	Batteries	Converter	System
Installation	1860	9117	10,350	4175	25,502
Replacement	0	0	0	4738	4738
O&M	648	1704	1118	0	3470
Fuel	0	0	0	0	0
Salvage	0	0	0	−787	−787
Total	2508	10,821	11,468	8127	32,924

WT/DG hybrid system

Cost(€)	WT	DG	Batteries	Converter	System
Installation	9117	534	2700	4175	16,526
Replacement	0	0	0	4738	4738
O&M	1707	127	292	0	2126
Fuel	0	4615	0	0	4615
Salvage	0	−113	0	−787	−899
Total	10,824	5164	2992	8127	27,107

WT/FC hybrid system

Cost(€)	WT	FC (2 kW)	Batteries	Converter	Reformer	Hydrogen tank	System
Installation	9117	3000	2400	4175	5000	3300	26,992
Replacement	0	0	0	4738	0	0	4738
O&M	1704	191	259	0	1246	0	3401
Fuel	0	0	0	0	2521	0	2521
Salvage	0	−386	0	−787	−377	−249	−1798
Total	10,821	2805	2659	8127	8391	3051	35,854

reformer and the hydrogen tank contribute to the total installation cost that reaches almost 70% of NPC.

The share of the installation cost is higher (85–90%) in the case of PV/WT system where no fuel is used.

7. Conclusions

This study evaluated different power generation alternatives to cover the electricity demand of a typical off-grid residence. Four configurations were investigated: PV–DG, PV–WT, WT–DG and WT–FC. Four locations with diverse wind and solar potential were considered and the application of hybrid power systems has been tested. Thus a total of 16 cases were examined and optimal solutions were analyzed in terms of Installation, Fuel, O&M and Replacement Costs and finally compared based on total Net Present Cost for an operation period of 20 years.

A combination of a conventional and a renewable unit is usually a balanced and optimal solution. Diesel Generators is an easy to install, mature developed technology that presents reliability and adaptability to load demand while Fuel Cells Technology is emissions-free, yet still considered expensive. Finally, the renewable unit must utilize the local wind or solar potential for best efficiency. Systems with solely renewable units are battery dependent and thus costly.

Under typical meteorological conditions throughout the area of Greece, WT–DG hybrid systems are considered the optimal solution for sites with a modest wind potential (average wind speed more than 3.5 m/s). A solar potential of around 1700 kWh/m^2 per year (which is typical for Greece) would be equivalent with the above wind potential (3.5 m/s) in terms of a PV–DG or WT–DG hybrid system.

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